METHOD AND APPARATUS FOR SINGLE BURST EQUALIZATION OF SINGLE CARRIER SIGNALS IN BROADBAND WIRELESS ACCESS SYSTEMS

PRIORITY APPLICATION

[0001] This application claims the benefit of U.S. Provisional Application No. 60/453,162, filed March 10, 2003, by Russell C. McKown, titled "Method and Apparatus for Single Burst Equalization," which is incorporated herein by reference.

BACKGROUND OF INVENTION

[0002] The development of wireless metropolitan area networks (WMAN's) and wireless local area networks (WLAN's) for broadband wireless access (BWA) to voice and data telecommunication services is an area of considerable economic and technological interest. The WMAN systems typically employ a point-to-multipoint topology for a cost effective system deployment. For example, proposed WMAN systems operating in the 2 to 6 GHz radio frequency (RF) range consist of base station cell tower sites with 3 to 6 antenna/transceiver sectors, with capacity goals of 40 to 80 Megabits per sector, and with coverage goals of 5 to 15 kilometer cell radius. Example WLAN systems include installations at areas both inside and outside of residences or businesses and public areas such as trains, train stations, airports or stadiums. These WMAN and WLAN systems can also be integrated to form a wide area network (WAN) that can be national or even global in coverage. WMAN systems are primarily discussed because they are technically the most challenging. However, the invention may also be used in broadband wireless access systems in general.

[0003] The primary problem in broadband wireless telecommunication is the considerable variation in the quality of the RF reception. The RF reception varies due to the type of terrain, due to the presence of obstacles between the base station and the subscriber station (SS), and due to the fairly high probability of receiving the same transmission by means of multiple RF propagation paths. The latter problem is referred to as "multipath" and the above set of reception problems is often collectively, and loosely, referred to as the non-line-of-sight

(NLOS) reception problem. When the SS is moving, there is the additional problem of Doppler induced channel variability. A robust NLOS BWA system for fixed or mobile subscribers is a technical challenge.

[0004] The WMAN systems of interest typically have RF channels that are the composite of multiple radio propagation paths over large distances. A consequence of these multipath propagation channels is that the received radio signal waveforms are distorted relative to the original transmitted radio signal waveforms. Prior art high data rate WMAN signaling technologies that are intended to mitigate the multipath performance degradations are orthogonal frequency division multiplexing (OFDM) and single carrier with frequency domain equalization (SC-FDE).

[0005] Figures 1 and 2 are diagrams of known OFDM and SC-FDE methods of transmitting and receiving signals with digital data modulations through dispersive propagation channels that impose some degree of multipath signal distortions. These diagrams emphasize the method specific signal processing elements and illustrate their dependence on FFT block processing.

[0006] FIG. 1 shows a block diagram illustrating certain processes performed by a system implementing the OFDM method. An inverse fast Fourier transform (inverse FFT) 110 transforms the data (symbols) 108 to be transmitted. Cyclic prefix insertion process 112 creates a serial output block with ends that are circular in content. These processes occur within OFDM transmitter 114. The transmitter output 115 passes through a propagation channel 116 to become input 117 to OFDM receiver 118. The method specific processes the OFDM receiver include a forward fast Fourier transform (FFT) process 120 that creates intermediate data symbols that have been distorted by the propagation channel, a process 122 to invert the channel and a process 124 to detect the original symbols, i.e., to provide the received data output 126. The OFDM symbol detection process 124 may, for example, include Viterbi decoding, symbol de-interleaving, and Reed-Solomon forward error detection/correction (FEC). The specific detection process 124 depends on the coding/interleaving that was applied to the transmitted data symbols 108.

[0007]   FIG. 2 shows a block diagram illustrating certain processes performed by a system implementing an SC-FDE method. The data symbols to be transmitted **128** are input to a preamble and cyclic prefix insertion process **130**. The preamble sequence has good correlation properties to support channel estimation and the cyclic prefix insertion creates circular output blocks to simplify receiver FFT operations. These processes occur within SC-FDE transmitter **132**. The transmitter output **133** passes through a propagation channel **134** to become input **135** to SC-FDE receiver **136**. The method specific processes in SC-FDE receiver **136** include a forward FFT **138** process to transform the signal into the frequency domain, a frequency domain filter to invert the channel **140**, an inverse FFT **142** to restore the signal to the time domain, and symbol detection **144** that provides the received data output **146**. The SC-FDE symbol detection process **144** may include a non-linear decision feedback equalizer (DFE) in addition to decoding and de-interleaving operations. As in the OFDM method, the detection process **144** may, for example, include Viterbi decoding, de-interleaving, and a Reed-Solomon FEC, or functionally similar operations, depending on the coding/interleaving that was applied to the transmitted data symbols **128**.

[0008]   Operationally, the OFDM and SC-FDE systems differ mainly in the placement of the inverse FFT. In the OFDM method the inverse FFT is at the transmitter to code the data into the sub-carriers. In the SC-FDE method the inverse FFT is at the receiver to get the equalized signal back into the time domain for symbol detection. Although FIG. 2 shows the SC-FDE signal to have a cyclic prefix insertion **130**, this is actually an option for SC-FDE that trades useable bandwidth for a slightly decreased number of receiver computations and a potential performance improvement. In the OFDM method, the cyclic prefix insertion **112** and the associated loss of useable bandwidth are mandatory.

[0009]   For high data rate single carrier (SC) systems, WMAN multipath RF channel distorts the signal by mixing data symbols that were originally separated in time by anywhere from a few symbols to a few hundreds of symbols. This symbol mixing is referred to as inter-symbol interference (ISI) and makes the SC wireless link useless unless equalization is performed. It is generally agreed that traditional time domain adaptive equalization techniques

are impractical to solve this problem since the computations per bit are proportional to the ISI span, which in the WMAN channels of interest can be hundreds of symbols. However, the FFT can be used to provide efficient frequency domain equalization for single carrier signaling. This is the basis of the single carrier frequency domain equalization (SC-FDE) method discussed above. SC-FDE is known to work well in terms of multipath mitigation and is practical in terms of transceiver computations per bit. A modern SC-FDE method is described by David Falconer, Lek Ariyavisitakul, Anader Benyamin-Seeyar and Brian Eidson in "Frequency Domain Equalization for Single-Carrier Broadband Wireless Systems", IEEE Communications Magazine, Vol. 40, No. 4, April 2002.

[0010]   For high data rate OFDM systems, WMAN multipath RF channels often result in severe spectral nulls. These spectral nulls make the OFDM wireless link useless unless interleaving and coding are performed. Coherent OFDM also requires equalization. However, OFDM with interleaving, coding, and equalization is known to work well in terms of maintaining a WMAN link in the presence of multipath and is equivalent to SC-FDE in terms of transceiver computations per bit. A critical comparison of the OFDM and SC-FDE techniques is given by Hikmet Sari, Georges Karam and Isabelle Jeanclaude in "Transmission Techniques for Digital Terrestrial TV Broadcasting", IEEE Communications Magazine, February 1995.

SUMMARY OF INVENTION

[0011]   The invention allows for use of time domain equalization in single carrier broadband wireless systems, thereby overcoming one or more problems associated with using traditional time domain equalization techniques and avoiding the disadvantages of OFDM and SC-FDE systems.

[0012]   An example of one use of a preferred embodiment of the invention is a receiver implementing a single carrier single burst equalization (SC-SBE) method. Such a receiver is capable of achieving near optimal reception of individual single carrier RF bursts. The receiver makes an estimate of the burst's propagation channel impulse response (CIR) and then uses a CIR-based coefficient computation process to obtain filter coefficients for a time domain equalization process. A subset comprising the most significant coefficients is selected for filters in the equalization process allowing more efficient implementation of the filters in the time domain.

[0013]   For example, if a time a minimum mean square error decision feedback equalizer (MMSE-DFE) used a MMSE-DFE filter computation process computes a sufficiently large number of coefficients for the DFE filters, i.e., the feed forward filter (FFF) and feedback filter (FBF), so that each filter spans the maximum anticipated length of the CIR.   For NLOS WMAN systems, this results in hundreds of computed coefficients for both the FFF and the FBF. In order to implement the filters efficiently, a coefficient selection process eliminates less significant computed FFF and FBF coefficients. The resulting FFF and FBF are "sparse" filters in that the sense that most of the taps in the filter delay lines do not have a filter coefficient. This allows the filters to be efficiently implemented in the time domain.

[0014]   The availability of time domain, sparse equalization filters avoid problems associated with the prior art OFDM and SC-FDE methods which use block processing FFT procedures. These problems include a large block granularity that limits bandwidth efficiency. In contrast, the SC-SBE method allows the bandwidth efficiency to be maximized.   The coefficient selection process improves the radio telecommunication link's performance for the majority of WMAN propagation channels. In the remaining WMAN channels the coefficient selection procedures assure that any performance degradation will be insignificant.

BRIEF DESCRIPTION OF DRAWINGS

[0015] FIG. 1 is a block diagram of the transmitter and receiver implementing a prior art OFDM method.

[0016] FIG. 2 is a block diagram of a transmitter and receiver that implement a prior art SC-FDE method.

[0017] FIG. 3 is a block diagram of a transmitter and receiver implementing a SC-SBE method with a coefficient selection process and sparse filter DFE.

[0018] FIG. 4 is a block diagram of a transmitter and receiver that illustrates the SC-SBE operations relative to other operations in a single carrier receiver.

[0019] FIG. 5 is a block diagram of an SC-SBE processor.

[0020] FIG. 6 is a block diagram illustrating a DFE performance based coefficient selection process with an exhaustive search.

[0021] FIG. 7 is a block diagram illustrating a DFE performance based coefficient selection process with amplitude based pre-selection.

[0022] FIG. 8 is a block diagram illustrating an amplitude threshold based coefficient selection process.

DETAILED DESCRIPTION

[0023]   A significant problem is created by both the OFDM and SC-FDE methods due to their reliance on the large block FFT operation. The problem, not recognized, is that the large block FFT operation restricts the efficiency of time division duplexing (TDD) and time division multiple access (TDMA) techniques. Modern TDD/TDMA techniques provide the opportunity for efficient use of a single RF channel for both downlink and uplink burst communication. For example, adaptive TDD/TDMA techniques, are defined in the IEEE Standard 802.16™-2001. In the adaptive TDD technique the position in time of the border separating a TDD frame's downlink and uplink traffic is adapted to best suit the relative amount of downlink and uplink traffic. It is well known that when properly implemented adaptive TDD is more spectrally efficient than the older frequency domain duplexing (FDD) technique which simply uses 2 RF channels, one for downlink and one for uplink. Proper utilization of TDD/TDMA techniques, however, requires flexibility with respect to the allowed (allocated) burst durations since the burst durations that are desired depend on the variable size of the data to be transferred.

[0024]   For WMAN systems, the OFDM and SC-FDE signaling techniques use an FFT whose size is typically in the 256 to 2048 sample point range. The problem is that the block FFT operations impose a large granularity on the TDD bandwidth allocation scheme that results in bandwidth inefficiency. The block restricted bandwidth allocation granularity is equivalent to the FFT size, in the range of 256 to 2048, or so, equivalent SC symbol time slots. This large TDD bandwidth allocation granularity significantly decreases the efficiency of a TDD/TDMA BWA system. Another problem with the OFDM and SC-FDE methods that results in bandwidth inefficiency is the periodic insertion of a cyclic prefix -- this directly turns valuable bandwidth into overhead.

[0025]   In contrast, methods and apparatus for single burst equalization of single carrier RF communications signals (SC-SBE), described in connection with Figures 3-7, do not require FFT operations or cyclic prefixes and provides greater flexibility in TDD bandwidth allocation, providing an allocation granularity/resolution of one single carrier symbol time slot.

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This allows the time-frequency bandwidth efficiency to be optimized in a SC-SBE based TDD/TDMA BWA system. The SC-SBE method takes advantage of a coefficient selection process and a DFE that uses time domain sparse filters.

[0026]   Note that the SC-SBE method and apparatus , described below in connection with Figures 3-7, has implementations at the system level of BWA systems, e.g., WLAN, WMAN and WAN systems, in components that make up the BWA systems, e.g., base station and subscriber station receivers, and in the circuits that make up the receiver or transceiver components. Unless otherwise represented, circuitry for performing the functions or processes referenced below may be implemented as hardware, software, or a combination of hardware and software. Implementation examples include software executing on a digital signal processor (DSP) or a general purpose computer, as well as logic elements executing in a field programmable gate array (FPGA) or an application specific integrated circuit (ASIC). Discrete functional blocks in the figures do not imply discrete hardware components.

[0027]   Figures 3, 4 and 5 illustrate SC-SBE concepts with reference to functional block schematic diagrams of example embodiments of transmitters and receivers. FIG. 3 is a block diagram of an example of a SC transmitter and SC-SBE receiver that facilitates a comparison with the OFDM and SC-FDE methods diagrammed in Figures 1 and 2. FIG. 4 is a block diagram of a SC-SBE receiver that illustrates the relation of the SC-SBE operations to other receiver operations, in particular the SC-SBE functions as a pre-processor to standard detection circuitry such as a Viterbi decoder. FIG. 5 is an example of a SC-SBE DFE with sparse, time domain filters.

[0028]   Referring to FIG. 3, the data symbols to be transmitted **158** by transmitter **162** are input to preamble insertion circuitry **160** that inserts a preamble symbol sequence having good correlation properties to facilitate an estimation of the propagation channel impulse response. The transmitter output **163** is an RF signal burst that passes through a propagation channel **164** to become the input **165** to receiver **166**.

[0029]   In receiver **166**, multipath channel equalization is accomplished with a sparse filter DFE **168**, described below. The input signal is delayed by a predetermined amount by delay circuit **170**. The delay is to allow time for the following to take place. A CIR estimate **173** is computed by process **172**. Estimates **175** of signal power and noise power are computed by process **178**. The signal power estimate is used to set an input gain **176** for the sparse filter DFE **168**. The MMSE-DFE filter coefficients **179** are computed by process **178** based on the CIR estimate **173** and the noise power estimate **175**. The filter coefficient subset **183** is selected by process **182** using methods described below. The selected filter coefficient subset **183** allows a high performance DFE **168** based on efficient time domain sparse filters.

[0030]   The DFE **168** provides channel equalized data **191** to symbol detection process circuitry **196** that performs symbol decoding and de-interleaving operations. The operations of symbol detection **196** are the inverse of the coding/interleaving operations applied to the transmitted data symbols **158**. Symbol detection **196** provides the received data output **197** that is of interest to the media access control (MAC) layer of the BWA system's base stations or subscriber stations.

[0031]   It is preferred that the processing delay **170** is less than the minimal RF signal burst duration which is on the order of 50 microseconds. This requirement insures that the receiver is capable of maintaining real time throughput at the TDD frame time scale which is on the order of 2 to 4 milliseconds.

[0032]   FIG. 4 is a block schematic diagrams that illustrates the SC-SBE processing circuitry relative to other operations in one exemplary embodiment of a receiver. In this example an SC-SBE circuit **198** is inserted between a conventional SC receiver front-end / timing recovery circuit **200** and a conventional symbol detection circuit **196**.

[0033]   Referring to FIG. 4, in the SC receiver front-end processing circuitry **200**, an RF signal is acquired by antenna **201** and processed by analog amplification, filtering and frequency down conversion **202** to provide a much lower frequency analog baseband or pass-band signal **203** that can be converted into digital samples by sampling circuitry **204** for

subsequent digital signal processing. Pulse shape filter 206 provides signal matched filtering that eliminates out of band noise and provides a signal 207 suitable for feed-forward timing recovery circuitry 208. Timing recovery in the SC receiver front-end processor 200 is desirable since it allows subsequent processing to be performed more efficiently using only one digitized sample per symbol. To achieve the timing recovery, the flow of the digitized burst signal is delayed by a predetermined amount by delay circuit 210. The delay is to allow time for symbol timing recovery circuitry 212 to compute the timing offset estimate 213. The timing estimate 213 controls interpolation circuitry 214 which outputs near optimally sampled data 215 to the SC-SBE circuit 198.

[0034]   As illustrated in FIG. 4, SC-SBE circuitry 198 can function as a pre-processor to a traditional symbol detection process or circuitry 196. For a more explicit example, symbol detection could be based on the transmit coding specified by the IEEE Standard 802.16a™-2003. In this case the symbol detection circuitry 196 would be a Viterbi decoder, a de-interleaver and a Reed-Solomon FEC, followed by a de-randomizer to recover the transmitted data of interest. The SC-SBE circuitry 198 does not depend on, nor require knowledge of, the type of symbol detection circuitry 196 that follows it. The detection circuitry 196 outputs the received data 197 that is sent to a MAC layer, not shown.

[0035]   Referring to FIG. 4, the CIR estimation process 172 in the SC-SBE circuit 198 can, for example, be performed with known non-parametric cross-correlation techniques in which the received preamble data is cross-correlated with the transmitted preamble data. Example preambles that are well suited for a cross-correlation based CIR estimation are the so called constant amplitude zero autocorrelation (CAZAC) sequences. The IEEE Standard 802.16a™-2003 specifies a CAZAC sequence for this purpose.

[0036]   The signal (S) and noise (N) power estimation process 174 can be designed based on a variety of known methods. For example, a preamble composed of multiple CAZAC sequences can be Fourier transformed over a time interval spanning two contiguous sequences. The power at even harmonics of the total period is an estimate of the signal plus noise (S+N) power, whereas the power at odd harmonics is an estimate of the noise power, N 175.

The signal only power can then be estimated by subtraction. The input gain 176 that is required by the sparse filter DFE 168 can be computed as the ratio of the desired signal level to the square root of the estimated signal power, S.

[0037]   The CIR estimate 173 and the noise power estimate 175 are input to the MMSE-DFE filter coefficient computation process 178.   Three alternative fast methods are known that can compute the filter coefficients 179 for an MMSE DFE from a CIR estimate and a noise power estimate.   These published, computationally efficient MMSE-DFE coefficient computation procedures are: Naofal Al-Dhahir and John M. Cioffi, *"Fast Computation of Channel-Estimate Based Equalizers in Packet Data Transmissions"*, IEEE Transactions on Signal Processing, pp. 2462-2473, 11, 43 (Nov. 1995);   Bin Yang, "An Improved Fast Algorithm for Computing the MMSE Decision-Feedback Equalizer",   Int. J. Electronic Communications (AEU), Vol. 53, No. 6, pp. 339-345 (1999); and N. R. Yousef and R. Merched, "Fast Computation of Decision Feedback Equalizer Coefficients", U.S. Patent Application 2003/0081668 (May 1, 2003). Each of these coefficient computation procedures can be used to efficiently compute the large number, e.g., hundreds, of filter coefficients 179 that define the long time span filters required by the DFE for WMAN systems.

[0038]   The reason channel equalization filters with long time spans are required is, that in order to be effective, the filters must span the maximum variability in the propagation delay in the multipath channel. This maximum variability is generally quantified by the 'delay spread' parameter. In order to characterize a multipath channel, it's CIR must be measured for delays somewhat larger than the delay spread. For example, in some WMAN systems, the multipath delay spread can exceed 10 microseconds and, typically, a single carrier signal having a 20 MHz bandwidth can be modulated with 16 million symbols per second. If the DFE filters for this SC system support the conventional minimum of one coefficient per symbol, this equates to greater than 160 coefficients per filter. It is straightforward to estimate the CIR over a 10 or more microsecond time span, for example using the above mentioned CAZAC cross-correlation technique.   Furthermore, the above mentioned three alternative fast coefficient procedures provide means of computing the coefficients 179. However, to directly implement filters with

such a large number of filter coefficients in the time domain would require an inordinately large amount of computation.

[0039]   Indeed, this excessive time domain computation requirement was the motivation for the known SC-FDE method diagrammed in FIG. 2.   However, as mentioned earlier, block FFT and cyclic prefix operations of the SC-FDE method create the problem of inefficient TDD/TDMA bandwidth utilization.   The SC-SBE method and apparatus solve the computation problem by selecting a subset of the coefficients for a time domain filter.   This time domain filter with sparsely populated coefficients (or "sparse" filter) provides approximation of the outputs of the time domain filter when all the calculated coefficients are used.

[0040]   Thus, the coefficient selection process simplifies the DFE filters and improves receiver performance.   Furthermore, a sparse time domain filter DFE allows efficient TDD/TDMA bandwidth utilization.   The coefficient selection process **182** examines the large number of computed MMSE-DFE coefficients **179** to identify a much smaller subset of coefficients **183** to be used by the DFE filters.   The sparse, time domain filters of DFE **168** efficiently implement these coefficients, avoiding the need for FFT filter techniques that result in TDD/TDMA inefficiency.

[0041]   FIG. 5 shows, in more detail, a schematic block diagram of an example SC-SBE processing unit **198** in order to illustrate the sparse, time domain filter DFE circuit **168**. Two outputs are shown from the coefficient computation process **178**: a complete set of feed forward filter (FFF) coefficients **180** and a complete set of feedback filter (FBF) coefficients **181**. The 'complete set of coefficients' refers to the MMSE-DFE coefficient computation **178** providing the number of coefficients required to span the maximum time lag of the CIR estimate **173**, which, given the above 20 MHz bandwidth WMAN system example, could result in 160 or more FFF and FBF coefficients, each. The coefficient selection process **182** inputs the complete set of coefficients, **180** and **181**, and outputs a considerably smaller number of selected coefficients, **184** and **185**, for use in defining a sparse FFF **186** and a sparse FBF **188**, respectively.

[0042]   The sparse FFF **186** and the sparse FBF **188** preferably have delay lines equal in length to the number of coefficients in the complete sets, **180** and **181**, say greater than 160 each. However, the number of non-zero coefficients in the sparse filters **186** and **188** are determined by the considerably smaller number of selected coefficients, **184** and **185**, for example, 16 each. The delayed received signal **171** is input to a multiplier circuit **194** having input gain **176** as the multiplier coefficient. This creates a signal amplitude scaled input **195** to the sparse FFF **186**. The amplitude scaling matches the amplitude of the signal component input to the FFF with the amplitude of the symbol decisions **193** that are input to the FBF **188**. This allows the sparse FFF output **187** and the sparse FBF output **189** to be directly input to summation circuit **190** to form the MMSE-DFE output **191**, the channel equalized signal that is input to the subsequent symbol detection process (not shown) . The MMSE-DFE output **191** is also input to symbol decision circuitry **192** that provides the symbol decisions **193** that are in turn input to the sparse FBF **188**.

[0043]   As drawn in FIG. 5, the sparse FFF and FBF filters, **186** and **188**, and the nonlinear symbol decision circuitry **192** constitute an example of a hard decision-decision feedback equalizer (H-DFE) structure. The H-DFE is well known and has been extensively analyzed. Alternative decision feedback equalizer (DFE) structures exist that can readily take advantage of the coefficient selection and sparse time domain filter elements of the SC-SBE method by simply substituting the sparse coefficient FFF and FBF filters defined above for the full coefficient FFF and FBF filters of the alternative DFE structure. An example of an alternative DFE structure is the soft decision / delayed decision integration of the DFE and Viterbi decoder, referred to as the S/D-DFE and developed in S. Lek Ariyavisitakul, and Ye Li, "Joint Coding and Decision Feedback Equalization for Broadband Wireless Channels", IEEE J. on Selected Areas in Communications, Vol. 16, No. 9, December, 1998. They indicate the S/D-DFE provides an approximate 3 dB performance improvement over the H-DFE. The performance advantage of the S/D-DFE structure over the H-DFE structure can be expected to be retained when these SC-SBE methods and apparatus are applied to both structures.

[0044]   The coefficient selection process **182** is a pruning of the complete set of coefficients that are output from the MMSE-DFE coefficient computation process **178**. The

coefficient selection process provides three major benefits: the ability to perform computationally efficient time domain equalization of channels having large multipath delay spreads; the ability to implement arbitrary TDD/TDMA bandwidth allocations using the minimal allocation granularity of one single carrier symbol; and improved overall receiver performance by avoiding the use of FFF and FBF coefficients which decrease the performance. The first benefit is based on the fact that sparse time domain filters can be used to efficiently implement the reduced set of selected filter coefficients, the number of selected filter coefficients probably needs to be less than 32. The second benefit is based on the fact that time domain filters, in general, allow arbitrary TDD/TDMA bandwidth allocations with the minimal granularity, e.g., one single carrier (SC) symbol. As discussed above, in contrast to the block processing frequency domain filtering techniques, standard time domain filtering does not impose block restraints on the TDD/TDMA allocation granularity, i.e., there is no additional computation cost for arbitrary start/stop allocations into a TDD time frame. The third benefit is improved overall receiver performance, in terms of the nature of the typical CIR of a WMAN system and the coefficient selection process.

[0045]   That the symbol error rate versus signal to noise ratio (SER versus SNR) performance can be improved with fewer taps is evident from the trivial example of the ideal additive white Gaussian noise (AWGN) channel. The DFE filter configuration that achieves the optimum performance for an AWGN channel is known to be equivalent to an all-pass filter. For the DFE to be equivalent to an all-pass filter requires that the tap selection algorithm select one FFF tap and zero FBF taps.

[0046]   That the performance is typically improved is evident in the nature of the WMAN RF propagation CIR. An optimally sampled CIR typically has a few clusters of coefficients with each cluster consisting of only a few significant coefficients. This sparsely clustered feature of a WMAN propagation channel CIR is due to the reflections near either the transmit or receive antennas being convolved with reflections far from either antenna. The desired FFF and FBF filters mimic this sparsely clustered feature of the WMAN CIR. Setting maximums of 16 FFF and 16 FBF coefficients is a conservative design for such channels. However, the maximum allowed number of coefficients is not critical and can be left up to the

implementation design engineer based on detailed engineering design considerations. For example, extensive computer simulations with accepted models for WMAN channels indicate that acceptable performance is obtained with the maximum number of allowed coefficients set anywhere between 8 and 32.

[0047]   This leaves the relatively rare cases where, in order to obtain the best DFE receiver performance, the WMAN CIR demands more than the allowed maximum of N_sparse = 16 or so coefficients each in the FFF and FBF filters. Fortunately, since the example coefficient selection processes discussed below select the most significant coefficients, the performance degradation in these cases will be slight. The slightly diminished DFE performance associated with having only the N_sparse most important coefficients is a good trade for what the coefficient selection process provides: efficient time domain equalization for NLOS WMAN channels with very large delay spreads and the bandwidth efficiency associated with arbitrary TDD allocations.

[0048]   For example, consider an SC-SBE processor that estimates the CIR and computes the MMSE-DFE coefficients based on a received preamble composed of a 256 symbol length Frank CAZAC as defined in the IEEE Standard 802.16a™-2003. In this example, the MMSE-DFE coefficient computation **188** outputs NF=256 computed FFF coefficients **180** and NB=255 computed FBF coefficients **181**. The coefficient selection procedure **182** inputs the complete set of computed coefficients and outputs, in this example at most 16 or so most significant FFF coefficients **184** and at most 16 or so most significant FBF coefficients **185**. With these selected coefficients, the sparse time domain FFF and FBF filters, **186** and **188**, efficiently span a delay spread of 512 symbols while retaining a TDD/TDMA allocation granularity of an individual symbol.

[0049]   FIG. 6 illustrates a schematic block diagram of one example embodiment of the coefficient selection process **182**. In this embodiment, the coefficients are selected jointly for the FFF and FBF filters based on the minimization of a DFE performance cost function. The received (RX) signal from timing recovery circuitry **215** is stored in an RX signal buffer **300**. The complete set of computed FFF and FBF coefficients, **180** and **181**, are stored in a computed

coefficient buffer **302**. Portions of the RX signal that contain known data **301** and a test FFF and FBF coefficient subset **303** are input to a sparse filter DFE computation circuit **304** that provides the DFE output **305** for input to a cost function computation circuit **306**. An example of a DFE performance cost function is the averaged error vector magnitude (EVM) that can be computed as the standard error of the DFE output relative to the known data. The DFE performance cost **307** is input to a minimization process **310** that identifies the coefficient selection that minimizes the cost subject to the constraints that the number of FFF coefficients cannot exceed N_FFF **308** and the number of FBF coefficients cannot exceed N_FBF **309**. The minimization process **310** can be thought of as performing a non-linear parameter estimation where the parameters being estimated are the addresses defining the coefficient subset, e.g., the test selection **311**, that minimizes the DFE performance cost **307**. The results of the cost minimization coefficient selection, i.e., the sparse coefficient vectors, **184** and **185**, are output to the sparse FFF and FBF filters, **186** and **188**, respectively.

[0050]   A potential problem with the above embodiment of the coefficient selection process **182**, as illustrated in FIG. 6, is that it is exhaustive in its search and may, consequently, require excessive time and computation. FIG. 7 illustrates a schematic block diagram of a modification of the DFE cost minimization based coefficient selection process that will reduce the search time and the associated computation. In this example embodiment, a pre-selection of the computed coefficients to be searched is performed based on the coefficient amplitude. The pre-selection consists of examining the computed FFF and FBF coefficients, **180** and **181**, to perform a selection **312** of the N_FFF largest amplitude FFF coefficients **313** and a selection **314** of the N_FBF largest amplitude FBF coefficients **315**. The N_FFF largest FFF coefficients **313** and the N_FBF largest FBF coefficients **315** are stored in a coefficient buffer **302** that defines the coefficient search space for the minimization process **310**. This pre-selection based on amplitude can be expected to have little effect on the DFE coefficient selection, i.e., the sparse coefficient vectors, **184** and **185**, since the exclusion of small amplitude filter coefficients generally have little effect on the filter output.

[0051]   FIG. 8 illustrates a schematic block diagram of a third example embodiment of the coefficient selection process **182**. This embodiment requires neither the

above iterative DFE performance cost minimization procedures nor any input of the received signal. In this embodiment the coefficients are selected based on the computed coefficient's amplitude satisfying two conditions: it is one of the N_FFF or N_FBF largest amplitude coefficients of the computed FFF or FBF coefficients, respectively; and it is bigger than $K*\sigma_F$ or $K*\sigma_B$, where σ_F or σ_B are the standard deviations of the NF-N_FFF smallest amplitude computed FFF coefficients or NB-N_FBF smallest amplitude computed FBF coefficients, respectively. Threshold parameter input 331, represented by the variable K, that provides protection against coefficient computation noise. NF and NB are the number of computed FFF and FBF coefficients, **180** and **181**, respectively. N_FFF and N_FBF, **308** and **309**, are the maximum number of non-zero FFF and FBF coefficients, **184** and **185**, respectively, to be selected.

[0052] As illustrated in FIG. 8, the computed FFF coefficients **180** are sorted by amplitude sorting circuitry **316** into the N_FFF largest coefficients **317** and the NF-N_FFF smallest coefficients **318**. Similarly, the computed FBF coefficients **181** are sorted by amplitude sorting circuitry **320** into the N_FBF largest coefficients **321** and the NB-N_FBF smallest coefficients **322**. The sets of smallest coefficients, **318** and **322**, are input to standard deviation circuitry, **324** and **326**, that output the standard deviations, σ_F **325** and σ_B **327**. The threshold comparison circuitry **328** selects the non-zero sparse filter FFF coefficients **184** as the subset of the N_FFF largest computed FFF coefficients **317** that are also greater than $K*\sigma_F$. Similarly, the threshold comparison circuitry **330** selects the non-zero sparse filter FBF coefficients **185** as the subset of the N_FBF largest computed FBF coefficients **321** that are also greater than $K*\sigma_B$.

[0053] Comparing the above three example embodiments of the coefficient selection process **182**, that are diagrammed in Figures 6, 7 and 8, the following observations can be made. All three embodiments input the complete set of computed coefficients, **180** and **181**, from the MMSE-DFE coefficient computation process **178** and output the selected filter coefficients, **184** and **185**, that contain at most N_FFF and N_FBF non-zero coefficients, respectively. The embodiments diagrammed in Figures 6 and 7 require input of the RX signal and perform an iterative non-linear cost minimization to achieve the coefficient selection. The embodiment diagrammed in Figure 7 performs a pre-selection based on the coefficient amplitude

to reduce the coefficient search space and the associated computations. The embodiment diagrammed in Figure 8 selects the coefficients based solely on the coefficient amplitude and can be expected to require the least amount of computation and be the simplest to implement.

[0054] The embodiment of Figure 6 is useful to illustrate the fundamental concept of the coefficient selection process **182** which is to eliminate computed coefficients so that the sparse time domain filters can be used in the DFE with either a DFE performance improvement or an insignificant performance loss. However, the embodiment of Figure 6 is anticipated to exhibit an excessive computational demand. On the other hand, embodiments of Figures 7 and 8 are practical implementations that have been extensively tested by means of computer simulation using accepted WMAN CIR models. Some of these simulation results are described in Russell McKown, "802.16e Proposal: Link Performance of WirelessMAN-SCa Mobile Subscriber Stations", IEEE c802.16e-03/19r2, 2003-03-11, which is incorporated herein by reference.